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Toward a Mobility-Driven Architecture for Multimodal Underwater Networking

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EXECUTIVE SUMMARY

Relying on autonomous underwater vehicles (AUVs) for ferrying data in an underwater network is an appealing approach for supporting a wide range of underwater networking applications. By equipping AUVs with *short-range, high-bandwidth* underwater wireless communications, which feature lower energy-per-bit cost than acoustic communications, the energy-usage efficiency and data throughput of a network servicing data-intensive applications can be significantly improved. Although data-ferrying is an attractive concept due to its simplicity, bringing this networking paradigm to fruition requires synergistic integration of a wide range of technologies that go beyond networking to incorporate, among others, energy recharging and management, and AUV path-planning and navigation. This report outlines functional layers that are necessary to accomplish the vision of a cohesive mobility-driven underwater networking architecture. Our focus is on networking functionalities, AUV path-planning algorithms, and estimation and forecasting tools required to develop effective network management and monitoring mechanisms.

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1. INTRODUCTION

Renewed interest in the undersea domain, sparked by applications including environmental monitoring, deep-sea exploration and exploitation, and undersea surveillance [1], has triggered the emergence of a new generation of undersea systems. These systems feature enhanced sensing and actuation technologies that allow them to gather large volumes of data, ranging from acoustic and environmental measurements to high-resolution imagery and video. Although they are equipped with enhanced wireless communication technologies, establishing reliable communications with these systems while they are deployed remains a challenge. Nevertheless, netted and seamless operation among them and between them and their operators are paramount to cope with the vastness of typical undersea operating areas and increasing demand for undersea data.

Underwater acoustic networks epitomize the current networking paradigm envisioned for the undersea. Acoustic communications (ACOMMs) enable long-range, low-bandwidth communications and, thus, make it possible for sparsely deployed systems to communicate. Although popular, underwater ACOMMs face formidable challenges that limit their capabilities and demand specialized protocols. They suffer from significant transmission path losses at high frequencies, long propagation delays, low and distance-dependent bandwidth, time-varying multi-path propagation, long interference ranges, and significant Doppler effects [2]. Furthermore, acoustic transmitters require properly designed media access control (MAC) protocols able to mitigate acoustic interference. Even when the latency and reliability level of ACOMMs are tolerable, their hefty energy-per-bit cost quickly renders them unaffordable for most battery-powered undersea systems attempting to transmit large volumes of data.

The prevailing paradigms for communicating with, and retrieving data from, undersea systems are based on:

- physical recovery, and
- a combination of data preprocessing, data compression, and either tethering to a surface buoy able to use radio frequency (RF) communications or using undersea ACOMMs to transmit the data.

These methods suffer several shortcomings from various financial, infrastructure, and communication perspectives. Physical retrieval of the systems is maximally efficient in terms of energy used for communications. However, its associated cost, demand for specialized recovery infrastructure, and the inherent disconnectedness of the system throughout the entirety of its mission render this approach inadequate for many applications. Data preprocessing and compression caters to improved connectivity when using ACOMMs or RF communications through a surface buoy, but continues to be confronted by the communications-related energy consumption. Moreover, in many situations buoys must be submerged to avoid interfering with maritime traffic, thereby adding the buoy surfacing system and its associated energy usage to the overall system infrastructure and energy requirements. Prompt access to undersea data, enhanced cooperation among undersea systems, and the extended operational lifetimes envisioned for future undersea missions further challenge the aforementioned paradigms and demand an enhanced underwater networking architecture.

The advent of short-range, high-bandwidth underwater wireless modes of communications coupled with enhanced autonomous underwater vehicle (AUV) technologies has given rise to a *mobility-driven* underwater networking paradigm [3], [4]. In this paradigm, battery-powered AUVs acting as data ferries visit each network node (undersea system) and use high-bandwidth underwater wireless communications for uploading (downloading) data from (to) them. High-bandwidth underwater wireless communications, including free-space optical communications (OCOMMs) [5], magnetic induction (MI) [6], and underwater RF communications [7], feature lower energy-per-bit cost than ACOMMs at short ranges and, thus, can reduce the energy consumption of the overall undersea network. Moreover, they enable netting systems located in areas where using ACOMMs alone has traditionally been problematic, such as shallow waters and surf zones (5- to 10-m depth) [6], [7]. An added benefit of this paradigm is that interference among undersea systems located even few meters away from each other is practically nonexistent due to the high attenuation that OCOMMs, MI, and RF signals experience underwater. Multiple transmitter-receiver pairs can transmit simultaneously and in close proximity without causing significant interference among themselves. The bulk of energy consumption for the network, which includes the undersea systems and the AUVs, is due to the AUVs' propulsion system. Thus, for a successful implementation of this paradigm it is paramount to consider how to route the AUVs, and where and when to recharge the AUV batteries so as to optimize their energy usage, specially since their recharge times are lengthy. From a network management perspective, recharging the AUV batteries leads to a dynamic network featuring a variable number of AUVs available to ferry data.

The contribution of this work is to propose a cohesive mobility-driven underwater networking architecture (MobArch) that captures unique aspects of the implementation of the mobility-driven networking paradigm as a viable underwater networking solution. We do not intend to provide a complete design and performance evaluation of a specific architecture for MobArch, but rather to discuss by example the major challenges and tradeoffs of designing such an architecture. MobArch features dynamic data routing and AUV path-planning algorithms able to cope with the dynamic nature of the network and the undersea environment. A successful implementation of MobArch relies on the availability and affordability of reliable technologies that support AUV battery recharging stations, AUV navigation and docking systems, underwater acoustic networking, and point-to-point high-bandwidth underwater wireless communications. While it requires a cross-layer design approach, our presentation emphasizes aspects of MobArch germane to the Network and Transport layers of the Open Systems Interconnection (OSI) model. Specific technology requirements are mentioned as required. Before introducing MobArch, the benefits of using a mobility-driven paradigm for networking are illustrated through an example.

2. BENEFITS OF NODE MOBILITY – A SAMPLE CASE

This section illustrates the benefits of using node mobility for underwater data collection through a simplified scenario. Admittedly, many challenges associated with a real implementation of the ensuing scenarios are disregarded to simplify the discussion. Nevertheless, considerations about deployment cost, maturity of OCOMM technologies, reliability of AUV navigation, and efficiency of undersea energy transfer also drive the selection of the most appropriate data collection approach for any practical scenario.

Assume that multiple battery-powered sensing nodes are deployed to collect undersea data. All data must be retrieved through a high-speed access point, hereafter named fusion center (FC). Figure 1a illustrates the underwater data collection system considered here. It comprises 100 nodes randomly located over a 34 km $\times$ 34 km square-shaped area with the FC located in its center. Each sensing node has a fixed data payload of 10 MB. The goal of the system is to gather all data to the FC for retrieval. The next two subsections illustrate the performance level achievable when using two different networking paradigms.

2.1 DATA RETRIEVAL WITH A STATIC UNDERWATER ACOUSTIC NETWORK

In this scenario, it is assumed that the sensing nodes form a connected acoustic network. Thus, there exists a path connecting the FC to every network node. For the network topology illustrated in Figure 1a, this is accomplished by presuming the availability of ACOMM links able to support transmission ranges up to 5 km. At a nominal transmission rate of 5,000 bps, transmitting the data payload over a single acoustic link requires roughly 4.4 hrs. Acoustic modems such as the Teledyne Benthos 920 Series[1], the LinkQuest UWM10000[2], and the EvoLogics S2C R 12/24[3] can support these data rate and range requirements. Using 40 W as a nominal acoustic transmission power, it follows that the associated price-per-bit of ACOMMs is 2.216 μWh/bit and the overall energy consumption to transmit 10 MB of data is 177.28 Wh.

FC relies on a shortest-path tree $\mathcal{T}$ rooted at the FC to gather all data (see Figure 1a). The tree $\mathcal{T}$ is a spanning tree, that is, the distance from the FC to any node $v \in \mathcal{T}$ is a geodesic between the FC and v over the acoustic network. Due to the long-range propagation of acoustics and since the communication medium is shared by all nodes, a MAC protocol must be used to mitigate interference and data losses due to collisions when transmitting the data towards the FC. However, including such a MAC protocol would compound our analysis of energy usage and data latency. In practice, data retransmissions due to packet errors and collisions, and the usage of a MAC protocol will cause the energy usage, data transmitted, and latency seen by the FC to increase. Although useful for the simplified analysis presented in this section, using a spanning tree for routing data towards the FC is neither necessary nor recommended. Alternative data routing approaches for underwater acoustic networks can be found in [8].

Instead of using a MAC protocol, it is assumed that: (a1) the ACOMMs links are error-free, (a2) all nodes can simultaneously transmit and receive data, and (a3) there is no acoustic interference among nodes. One quickly realizes that nodes with lower depths in $\mathcal{T}$ relay more data towards the FC (see Figure 1b). Hence, they use more energy for acoustic communications and deplete their batteries sooner than other nodes. For instance, Node 24 transmits its own data and relays data from 41 other nodes. It consumes 7.44 kWh on acoustic communications alone. The entire network consumes 90.06 kWh, all of it provided by the, often non-rechargeable, batteries of the sensing nodes. In terms of data latency, gathering all data at the FC takes a staggering 7.78 days. Due to (a1)–(a3), these performance values define *optimistic* lower

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[1] Benthos 920 Series ATM 925 supports data rates between 140 and 15,360 bps at 2–6 km ranges. Data retrieved fromhttp://teledynebenthos.com/product/acoustic_modems/920-series-atm-925 on February 2, 2016.

[2] LinkQuest UWM10000 supports data rates up to 5,000 bps at ranges up to 10 km. Data retrieved from http://www.link-quest.com/html/models1.htm on February 2, 2016.

[3] EvoLogics S2C R 12/24 supports data rates up to 9,200 bps at ranges up to 6 km. Data retrieved fromhttps://www.evologics.de/en/products/acoustics/s2cr_12_24.html on February 2, 2016.

bounds on the energy usage, data volumes transmitted, and latency observed at the FC. In a real underwater acoustic network deployment, it is expected that all these values will increase in magnitude according to the specific MAC protocol used and the bit-error rates observed in the acoustic channel.

2.2 DATA RETRIEVAL USING AUVS

Instead of using the aforementioned data collection framework, this section uses a flotilla of five AUVs to collect all data and deliver them to the FC. The sensing nodes are partitioned into five clusters. Each cluster is assigned to an AUV for service. AUVs are launched from the FC and use a *nearest-neighbor* rule to decide what node in their assigned cluster to visit next. Once all nodes have been visited, each AUV returns to the FC and delivers the data. All nodes and AUVs use OCOMMs to exchange data.

For this example, REMUS-600[4] AUVs with a 5.2-kWh battery are considered. Their mission duration capability of up to 70 hrs enables them to travel up to 388.1 km at a nominal speed of 1.54 m/s (3 knts). The OCOMMs system considered features a bit rate of 10 Mbps at a range of 10 m and uses 5 W of power to transmit. Hence, its associated cost-per-bit is 138.89 pWh/bit. With these characteristics, OCOMMs consume 11.11 mWh to upload/download 10 MB of data. The latency of the data collection system depends on the AUV travel times and data exchange times. At 10 Mbps, it takes 8 s to upload (download) 10 MB of data from (to) any node. The AUV-cycle lengths for the node partition shown in Figure 1 range between 65.56 and 92.18 km. Disregarding ocean currents, an AUV moving at 1.54 m/s completes the shortest cycle in 11.83 hrs and the longest cycle in 16.63 hrs, and consumes 0.88 and 1.24 kWh, respectively. Thus, it takes 16.63 hrs for all the data to arrive at the FC. Each AUV consumes less than 25% of its battery capacity when collecting data from its assigned set of nodes. The entire system consumes 5.26 kWh, nearly all of it provided by the rechargeable batteries of the AUVs. In this case each AUV can complete its cycle without recharging its battery. When ACOMMs alone were used to collect the data, two nodes needed battery capacities larger than 5.2 kWh to satisfy the energy requirements of their own ACOMMs.

Different from the scenario described in the previous section, increasing the amount of data to be collected per node does not significantly impact the overall energy consumption and latency of the system. Here, the latency and energy consumption due to OCOMMs are dominated by the AUV travel times and AUVs' energy consumption associated to their propulsion systems. Ocean currents will impact AUV energy consumption and should be carefully considered when selecting AUV trajectories.

[4]The REMUS 600 features a 5.2 kWh rechargeable lithium ion battery, supports speeds of up to 2.6 m/s (5 knts), and can yield up to 70 hrs of endurance. Data retrieved from *REMUS 600 Autonomous Underwater Vehicle* at http://www.km.kongsberg.com on February 2, 2016.

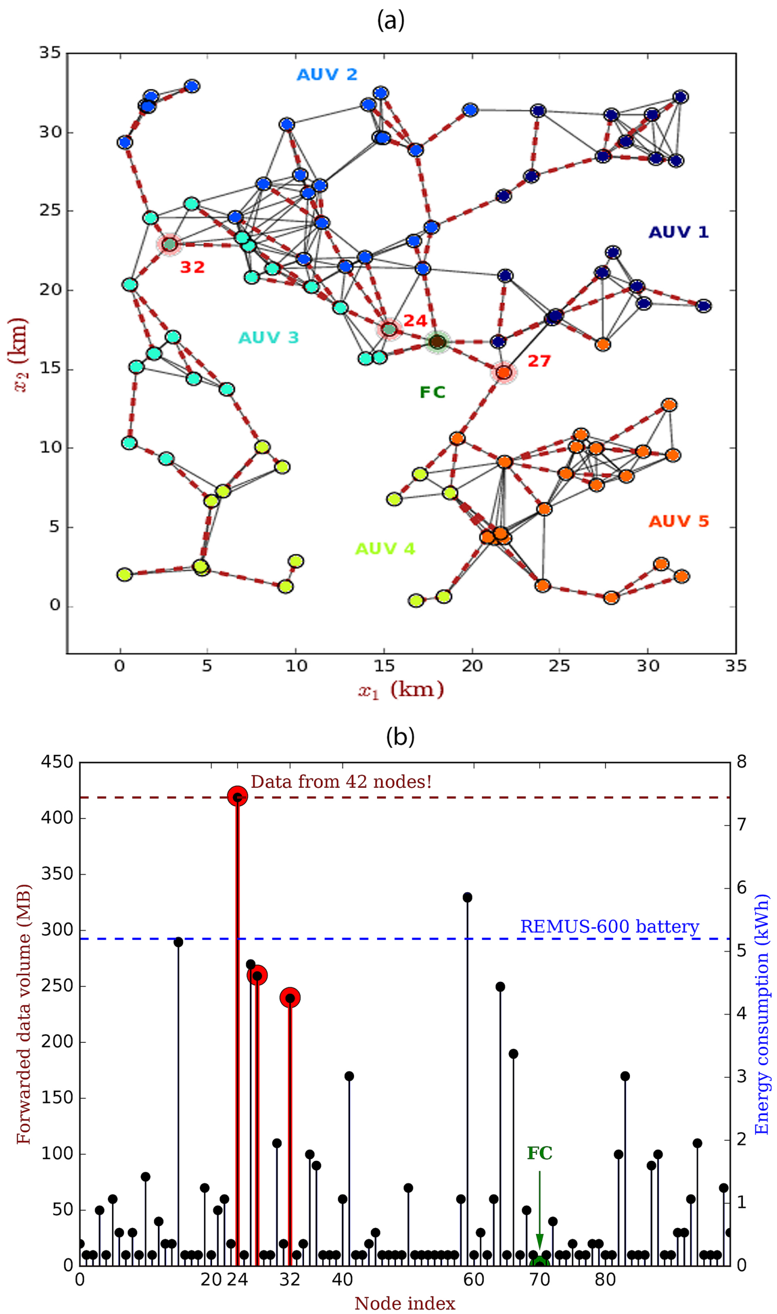

Figure 1. Illustration of a data collection system with 100 nodes. Each node has 10 MB of data that must be gathered at the FC for retrieval. (a) Topology of a fixed underwater acoustic network used to move all data towards the FC as described in Section 2.1. The shortest-path tree $\mathcal{T}$ rooted at the FC is shown (in dashed red lines) overlaid over all available acoustic links (shown in solid gray). This figure also shows the partitioning, illustrated by the node color, of the sensing nodes into 5 groups as described in Section 2.2. Each cluster is served by an AUV that collects all data from the sensing nodes. Radial sectors, with central angle of 72°, centered at the FC were used to defined the partitioning. (b) Summary of transmitted data and energy consumption per node after all data have been gathered at the FC through the acoustic network as described in Section 2.1. Red and green circles correspond to highlighted red and green nodes in (a).

3. MOBARCH'S PHYSICAL REQUIREMENTS

Motivated by the example presented in the previous section, this section develops the rationale for MobArch, and introduces its physical building blocks and supporting infrastructure requirements. The ensuing presentation underscores the physical blocks needed by MobArch and the technology challenges their implementation entails.

The idea of using mobile nodes as data ferries to enable connectivity in an otherwise disconnected network was first introduced in the context of disruption-tolerant networking (DTN) [9], and was quickly adopted by the underwater networking community [3], [4]. Despite its conceptual simplicity, developing all necessary technologies to enable this form of underwater networking has proven difficult in part due to the breadth of engineering disciplines involved and the challenges associated with deployment and operation of undersea systems. Works focusing on the data-retrieval problem have considered multiple AUV path-planning problem formulations [4]. However, the development of a cohesive networking architecture capturing the intertwine among data networking functionalities, networkwide control requirements, and AUV path-planning and battery-recharging demands remains insufficient.

MobArch's vision is to develop an underwater networking architecture that naturally integrates AUV and data management. MobArch comprises several building blocks as illustrated in Figure 2. The overall network is comprised by multiple disconnected subnetworks, where nodes in different subnetworks are presumed to be disconnected. Beyond being out of ACOMMs range, this is a valid assumption when the volume of data to be exchanged between nodes in different subnetworks is so large that ACOMMs are rendered impractical. A subnetwork can even be a singleton representing a high-speed access point to, e.g., an above-water RF network or a fiber optic cable. Each subnetwork is assumed to be *connected*. All intra-subnetwork data traffic is handled through the local communications infrastructure.

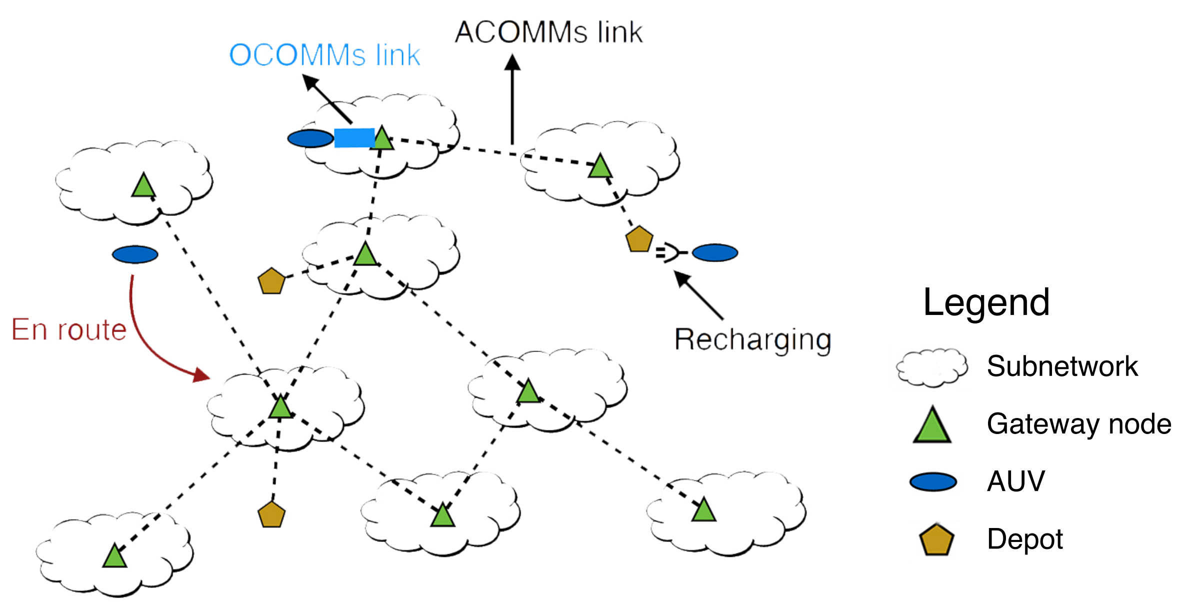

Figure 2. Network model considered by MobArch. Each subnetwork (cloud icons) has an associated gateway node (green triangles) that funnels all data leaving and entering the subnetwork. AUVs (blue spheres) ferry data between subnetworks and periodically recharge their batteries at the depots (gold pentagon). Gateways form a connected acoustic network that defines the acoustic backbone of MobArch.

Each subnetwork has an associated high data-storage capacity node, known as the *gateway*. The gateway behaves as a *throwbox* where data can be stored for extended periods while on their way to their destination. Data to be transmitted (received) to (from) other subnetworks are funneled through the gateway. AUVs can also drop data at a gateway where they wait to be advanced toward their destination by another AUV. It is assumed that gateways are able to use both ACOMMs and high-bandwidth, underwater wireless communications. Gateways can represent cluster heads that define a hierarchical networking architecture.

A flotilla of AUVs is used to collect (deliver) data from (to) the gateways. AUVs are equipped with high-speed, wireless communication technology that allows them to communicate with the gateways. They also feature high data-storage capacity so that they can collect and maintain data from multiple gateways. AUVs are battery-powered and, thus, they need to be periodically recharged. To this end, special AUV-recharging nodes called *depots* are also deployed. Note that MobArch requires the deployment of navigation, homing, and docking systems to enable AUVs to locate, navigate toward, and possibly dock at gateways and depots.

Depots are visited by AUVs to recharge their batteries. They are equipped with ACOMMs and, for the purpose of this work, are presumed to always be able to satisfy the energy demands of the AUVs. Nevertheless, depots have a finite number of recharging ports. Thus, if multiple AUVs try to concurrently recharge their battery at the same depot, some of them may have to wait until a recharging port becomes available. Depots must support homing and docking functionalities for AUVs so that battery recharging can take place.

Within MobArch, ACOMMs continue to play a fundamental role as the enabler of long-range connectivity among gateways. Gateways and depots form a *connected* acoustic network which is used for collecting and disseminating control data from and to the entire network. From a networking vantage point, this enables MobArch to separate the control and the data planes. The control plane corresponds to the acoustic *backbone* network[5] comprising gateways and depots. Similarly, the data plane corresponds to the *virtual* links instantiated by the AUVs. This separation enables the control plane to use ACOMMs to disseminate service policy adjustments to the entire network and collect networkwide status data for developing management and monitoring tools without being affected by the payload data volumes. The data plane uses the AUVs and a high-speed mode of communications to transport large data volumes at reduced energy and latency costs. Note, however, that such connectivity assumption limits the maximum separation possible among gateways which may render MobArch unsuitable for very sparse network deployments, and require the deployment of acoustic relays between gateways.

[5]Backbone network refers to the infrastructure that connects all gateways and depots for transporting control data. Different from its traditional use in computer networks, it is neither presumed that the backbone network features high-capacity links nor that it will transport large data volumes.

4. MOBARCH'S FUNCTIONAL LAYERS

A goal of MobArch is to support large-volume data exchanges among subnetworks while providing a prescribed quality-of-service (QoS) level. This goal demands the design of networking protocols, AUV path-planning algorithms, and monitoring tools able to provide delivery, throughput, and delay guarantees for all network traffic while allowing some level of management and supervision.

Networking protocols within MobArch will be responsible for data routing and gateway memory management. They will rely on DTN technologies to provide end-to-end (source-gateway to destination-gateway) delivery guarantees. Moreover, they can influence the selection of the paths to be followed by AUVs according to network-related parameters such as data prioritization and memory usage at both gateways and AUVs. Likewise, AUV paths can influence data-routing and gateway-memory management policies. From a management and monitoring perspectives, one would like to have assured and non-interrupted access to all network components. Unfortunately, collecting networkwide state information regularly is impractical due to the disconnected nature of the environment and the high cost associated with collection of control data through the acoustic backbone network featured by MobArch. However costly, some minimum level of network-state control information needs to be exchanged to capture the dynamics of the underlying communication network with AUV management and operation.

The main functional layers of MobArch are illustrated in Figure 3. Although they require a cross-layer design approach to access the status of AUVs and gateways, their functionalities can be broadly associated with those of the OSI's Network and Transport layers. The following subsections describe the various MobArch layer functionalities and their interactions. Note that MobArch does not require specific Physical and Data Link layer technologies for point-to-point communications.

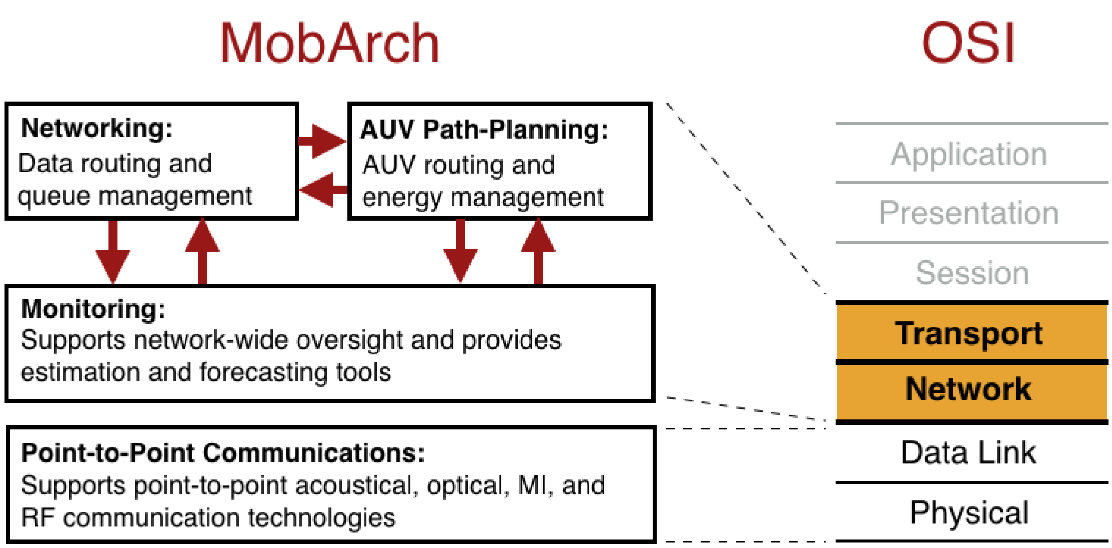

Figure 3. Main functional layers of MobArch and their correspondence to high-level functionalities defined in the classical OSI model.

4.1 NETWORKING LAYER

This layer provides network and transport protocols to the acoustic backbone. These protocols are mindful of the energy constraints of the gateways. Thus, they are developed so that excessive packet replication and interference among gateways is avoided. The *known* topology of the acoustic backbone can be exploited to develop advanced routing algorithms [8]. Likewise, using advanced MAC protocols can improve control-data throughput and reduce data latency in the acoustic backbone [10].

The Networking Layer also defines the routing of the network data through the links instantiated by the AUVs. As illustrated by Figure 4, the path followed by an AUV may not reach the gateway to which some of its data payload is routed. In this case, the AUV relays that portion of its data payload to an intermediate gateway where they are temporarily stored. Eventually another AUV will pick up the data and advance them towards their destination. Packet routing technologies developed for DTN can be leveraged to enable AUVs to establish routes, that is, *virtual* paths, for the data. These routes can be designed bearing in mind latency-minimization and throughput-maximization objectives depending on the underlying applications running on the network.

Protocols for data prioritization and storage-queue management at the gateways are also managed by this layer. When a gateway faces a data overflow, data priorities and time-to-live scores can be used as a metric for a queue-management policy that, in the same spirit of MaxProp [9], judiciously discards outdated and low-priority data first. Similarly, data priorities and gateway storage-queue metrics can be used to *dynamically* influence the AUV path-planning algorithms. They will, for example, steer AUV routes towards regions in which larger volumes of data need transport.

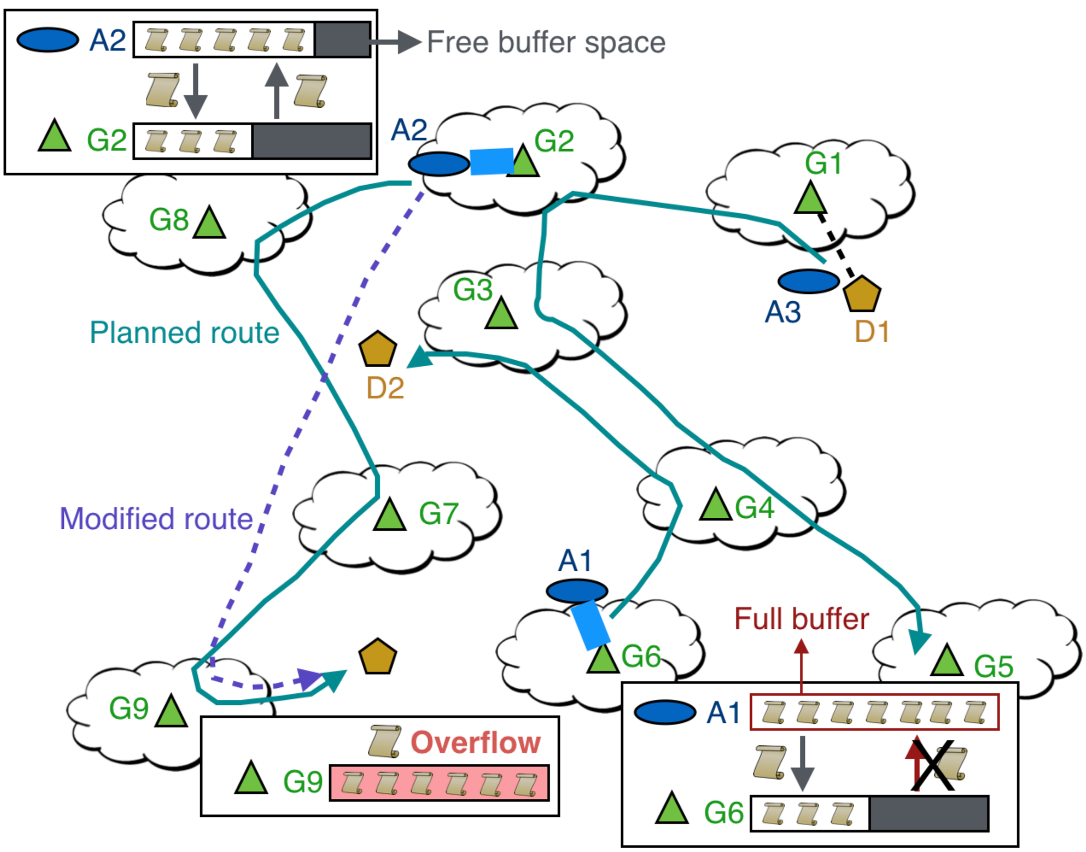

Figure 4. Sample functionality of the Networking Layer. A2 collects all data from G2 that are addressed to G8, G7, and G9. It also downloads to G2 all data in its buffer that are addressed to G3, G4, and G5. Since A3 will visit G2, A3 may be able to pick up those data from G2 and deliver them to their destination. A1's buffer is full; thus, it can only deliver data. G9 is overflowing. It uses the acoustic backbone (shown in Figure 2) to request an AUV visit sooner than it is currently planned. Since the data-storage buffer of A1 is full, it is decided that A2 should modify its planned route and visit G9 directly after leaving G2, before visiting G7 and G8. Meanwhile, G9 uses its local buffer-management policy to discard low-priority and outdated data first.

Lastly, this layer is also responsible for protocols to efficiently broadcast, multicast, anycast, and geocast data. Here, higher efficiency is achieved by protocols that reduce the number of copies of the data that are propagated through the network, and the corresponding bandwidth and energy resources used in doing so. AUVs will be the custodians of the data and will decide when and where to replicate them. Properly designed multicast protocols will reduce the overall communication load of the network when, for example, updating the firmware of a set of sensors, remotely activating multiple underwater nodes, and delivering updated navigation or tasking information to a group of nodes.

4.2 AUV PATH-PLANNING LAYER

This layer deals with the problem of AUV path planning for ferrying data across the network, which is related to the celebrated vehicle routing problem (VRP) [11]. Since VRP is known to be an NP-hard problem, a plethora of heuristics have been developed within the area of operational research to solve it, see [11], [12] and references therein. The underwater mobility-driven networking paradigm considered by MobArch brings new challenges. AUVs must collect and deliver data from multiple gateways while being aware of their own data-storage and energy constraints. Moreover, they should do so while facing limited connectivity to the acoustic backbone and responding to the underlying dynamics of the network and the environment. The latter includes changing data priorities and QoS requirements, varying ocean currents affecting AUV energy consumption and travel times, and network infrastructure changes due to node failures and battery-recharge times.

Fixed data-ferrying paths can be chosen by leveraging tools developed for the traveling salesman problem and its manifold multi-agent extensions [4]. Although appealing because they lead to reduced control-data exchanges and allow gateways to depend on *scheduling* strategies for ferrying data and designing their local queue-management policies, these approaches fail to respond to the underlying network dynamics. In fact, they disregard QoS provisioning to the network, which goes beyond facilitating network connectivity. Moreover, most of these approaches are *episodic* and presume that fixed data volumes are periodically collected per node. In the context of MobArch data arrive to the gateways at rates that feature spatiotemporal variability, thus rendering fixed data-ferrying paths inadequate.

A suitable solution for AUV path-planning captures the dynamics of the AUV-battery energy levels, the AUV-battery recharge times, and the data-storage capacity limits of the AUVs and the gateways. Moreover, it interacts with the Networking and Monitoring Layers so as to responds to dynamic network demands, as illustrated by Figures 4 and 5, and judiciously plans how to assign AUVs to depots for battery recharge so as to avoid long queue-waiting times. The AUV Path-Planning Layer also influences the Networking Layer by providing AUV-route estimates which can be used for routing data along multiple gateway hops. Dynamic AUV path-planning approaches that consider energy consumption, data losses, and latency in the context of underwater data retrieval have been recently developed in [13, [14].

Enabling dynamic AUV path-planning demands a minimum level of coordination across the entire network, which can be achieved through the acoustic backbone. Despite the bandwidth and latency challenges associated to ACOMMs, the sporadic frequency with which AUVs visit gateways and depots, and the relative "long" (for acoustic signal propagation) AUV travel-times between them allows enough time for collecting all control-data required, making a routing decision, and delivering that decision back to the AUVs [13].

4.3 MONITORING LAYER

This layer delivers management and monitoring tools for the entire network. It serves as a supporting layer for both the Networking and the AUV Path-Planning Layers by enabling them to capitalize on a global view of the network to, e.g., make data-routing decisions. Ideally, one would like to measure the network-state everywhere and distribute that information so as to make fully informed decisions regarding network operation. However, transmitting all this information through the acoustic backbone is impractical.

A similar challenge has been faced by IP networks for which acquiring networkwide status indicators quickly becomes a formidable task as the network size grows. Instead of measuring everywhere, approaches using only a subset of network-measurements to predict the networkwide status have been proposed, see [15] and references therein. These tools can be leveraged by network operators who are interested in estimating and forecasting metrics such as the amount of data expected at each gateway, data-delivery latencies, gateway energy usage, and data losses due to buffer overflows.

The resulting estimation algorithms capitalize on the underlying network structure given by the data routes and AUV paths defined by the Networking and AUV Path-Planning Layers, respectively. Collecting a subset of measurements for evaluating the network-status estimators can be done on demand, that is, triggered in response to a monitoring request or by a protocol in the Networking and AUV Path-Planning Layers (cf., Figure 5). Network operators can also use these measurements for constructing forecasting models. A related alternative bestows each gateway with the responsibility of maintaining local forecasting models.

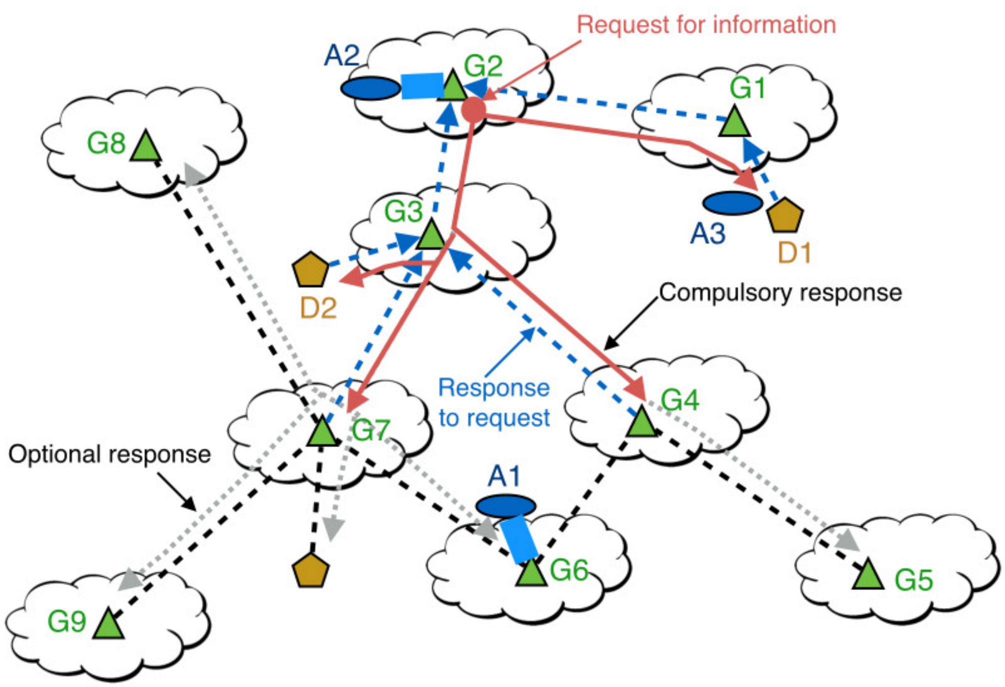

Figure 5. Illustration of an information request triggered by the dynamic AUV Path-Planning Layer. It occurs as soon as A2 completes its data exchange with G2 and is ready to be routed. G2 can broadcast a request for control data, or send a multicast message to neighboring gateways and depots only. Although control data from other parts of the network are also relevant, it is not necessary to collect them at G2. Instead, the AUV Path-Planning Layer relies on the networkwide estimation and forecasting tools provided by the Monitoring Layer to estimate and forecast necessary network metrics. Since AUVs en route may not be reachable through the acoustic backbone, all information requests are addressed to gateways and depots only.

Each gateway will use its historical status data to train parametric models able to forecast variables of interest at multiple resolution levels so as to enable reliable short-term and long-term forecasts. The parameters defining this models are periodically collected by the operator who couples them with the *known* network topology to build networkwide forecasting models.

5. FUTURE EXTENSIONS OF MOBARCH

Several research directions to broaden the scope of MobArch are possible. One could remove the acoustic backbone requirement and have AUVs transport both control and payload data. Control data is now disseminated through the network by AUVs that rely on gateways as intermediate storage nodes. Although this strategy ensures that control data eventually propagate through the network, their propagation rate may be slow and is tied to the speed of the AUVs. The network would have to rely heavily on estimation and forecasting tools provided by the Monitoring Layer since measurements of the current network status may not always be available.

In this new paradigm, *distributed* and dynamic AUV path-planning functionalities become essential to continue supporting the main services provided by the AUV Path-Planning Layer. Their goal is to enable AUVs to plan their paths based on the information that they acquire when visiting gateways and depots only. To this end, AUVs leverage tools provided by the Monitoring Layer to construct and maintain networkwide prediction models that can be used for estimation and forecasting of networkwide parameters.

MobArch can also incorporate mobile gateway nodes and subnetworks in which the role of the gateway can be performed by multiple nodes. Each subnetwork may use a different node as a gateway according to a locally defined schedule chosen to maintain homogeneous energy consumption among all nodes. In this case, the Networking Layer must support a gateway-location discovery protocol that allows AUVs to find the geographical location of the current subnetwork gateway. ACOMM exchanges between AUVs and subnetwork nodes other than gateways become necessary for AUVs to learn the gateway identity and location.

6. SUMMARY

MobArch was introduced in response to the practical demands of the mobility-driven underwater networking paradigm. Its architecture underscores the importance of judiciously using multiple underwater wireless communication modes for networking, enabling dynamic AUV path-planning for choosing data-ferrying paths, developing advanced networkwide monitoring tools, and synergistically integrating AUV and data routing. Although the benefits in terms of energy usage and data latency achievable when using MobArch can be significant, realizing the vision of a mobility-driven underwater networking paradigm is challenging due to the various technology challenges that must be surmounted. Nevertheless, broad scientific interest in the undersea and ongoing technology developments continue to pave the way towards accomplishing the vision on MobArch.

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14. ABSTRACT

Relying on autonomous underwater vehicles (AUVs) for ferrying data in an underwater network is an appealing approach for supporting a wide range of underwater networking applications. By equipping AUVs with short-range, high-bandwidth underwater wireless communications, which feature lower energy-per-bit cost than acoustic communications, the energy-usage efficiency and data throughput of a network servicing data-intensive applications can be significantly improved. Although data-ferrying is an attractive concept due to its simplicity, bringing this networking paradigm to fruition requires synergistic integration of a wide range of technologies that go beyond networking to incorporate, among others, energy recharging and management, and AUV path-planning and navigation. This report outlines functional layers that are necessary to accomplish the vision of a cohesive mobility-driven underwater networking architecture. Our focus is on networking functionalities, AUV path-planning algorithms, and estimation and forecasting tools required to develop effective network management and monitoring mechanisms.

15. SUBJECT TERMS

autonomous underwater vehicles; underwater network; short-range, high-bandwidth underwater wireless communications; data ferrying; energy recharging and management; networking functionalities, AUV path-planning algorithms, estimation and forecasting tools

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